

Dynamical parallax of σ Ori AB: mass, distance and age

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ABSTRACT

The massive OB-type binary σ Ori AB is in the centre of the very young σ Orionis cluster. I have computed the most probable distances and masses of the binary for several ages using a dynamical parallax-like method. It incorporates the *BVR_IH*-band apparent magnitudes of both components, precise orbital parameters, interstellar extinction and a widely used grid of stellar models from the literature, the Kepler's third law and a χ^2 minimisation. The derived distance is 334^{+25}_{-22} pc for an age of 3 ± 2 Ma; larger ages and distances are unlikely. The masses of the primary and the secondary lie on the approximate intervals 16–20 and 10–12 M_{\odot} , respectively. I also discuss the possibility of σ Ori AB being a triple system at ~ 385 pc. These results will help to constrain the properties of young stars and substellar objects in the σ Orionis cluster.

Key words: stars: individual: σ Ori – stars: binaries: close – open clusters and associations: individual: σ Orionis

1 INTRODUCTION

The Trapezium-like system σ Ori, that illuminates the enclosure of the Horsehead Nebula, is the fourth brightest star in the young Ori OB 1 b association. The multiple system is composed of at least five early-type stars (Burnham 1892; Greenstein & Wallerstein 1958; van Loon & Oliveira 2003; Caballero 2007b). The two hottest components, σ Ori A and B (O9.5V and B0.5V), are separated by only ~ 0.25 arcsec and were for a long time “the most massive visual binary known” ($M_A + M_B \sim 25 + 15 M_{\odot}$; Heintz 1974). Although the binary has not yet completed a whole revolution, the orbital parameters are relatively well determined (Hartkopf, Mason & McCalister 1996; Heintz 1997; Horch et al. 2002). It has been suggested that σ Ori AB is a hierarchical triple, being the primary a short-period, double-line spectroscopic binary (Frost & Adams 1904; Henroteau 1921; Miczaika 1950; Bolton 1974; Morrell & Levato 1991). However, a large amount of accurate, comprehensive spectroscopic investigations have failed to confirm this hypothesis (Heard 1949; Conti & Leep 1974; Humphreys 1978; Bohannan & Garmany 1978; Garmany, Conti & Massey 1980; Simón-Díaz & Lennon, priv. comm.).

The σ Ori system is located in the centre of the well-known σ Orionis open cluster. The proper motions, radial velocities and spacial distribution of stars in this cluster strongly suggests a physical association between σ Ori itself and the young cluster (Zapatero Osorio et al. 2002a; Caballero 2007a, 2007c – see also Jeffries et al. [2006], who

discovered a second older and kinematically and spacially distinct population). Because of its youth, comparative nearness and low extinction, the cluster has become the richest hunting ground for brown dwarfs and planetary-mass objects in the whole sky (Béjar et al. 1999; Zapatero Osorio et al. 2000, 2002b, 2007). There is plentiful material in the literature about this cluster, covering topics like the initial mass function down to a few Jupiter masses (Béjar et al. 2001; González-García et al. 2006; Caballero et al. 2007), jets and Herbig-Haro objects (Reipurth et al. 1998; Andrews et al. 2004), the frequency of accretors and discs (Zapatero Osorio et al. 2002a; Oliveira, Jeffries & van Loon 2004; Kenyon et al. 2005; Oliveira et al. 2006; Hernández et al. 2007; Caballero et al. 2007), the X-ray emission from young objects (Walter et al. 1997; Sanz-Forcada et al. 2004; Franciosini, Pallavicini & Sanz-Forcada 2006) or their photometric variability (Caballero et al. 2004; Scholz & Eislöffel 2004). The most used values of heliocentric distance and age of the σ Orionis cluster are $d \sim 360$ pc and ~ 3 Ma (Brown, de Geus & de Zeeuw 1994; Perryman et al. 1997; Zapatero Osorio et al. 2002a; Oliveira et al. 2002). There is a consensus in the literature that the cluster is younger than 8 Ma and older than 1 Ma. There is, however, a strong divergence of opinion on the heliocentric distance. Caballero (2007a) compiled determinations in the literature of the distance to the σ Orionis cluster from the 352^{+166}_{-168} pc from *Hipparcos* parallax to almost 500 pc from colour-magnitude diagrams.

Apart from the uncertainties of theoretical isochrones at very young ages, the derivation of the initial mass function of the cluster is strongly affected by the uncertainty in the actual age and heliocentric distance (Jeffries et al.

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Table 1. Photometry of σ Ori A and B from the literature.

Band		σ Ori A	σ Ori B	References
<i>B</i>	[mag]	3.85 ± 0.05	5.18 ± 0.05	Ca07a
<i>V</i>	[mag]	4.10 ± 0.03	5.34 ± 0.10	tBr00
<i>R</i>	[mag]	4.15 ± 0.04	5.49 ± 0.13	tBr00
<i>I</i>	[mag]	4.41 ± 0.04	5.66 ± 0.16	tBr00
<i>H</i>	[mag]	4.81 ± 0.10	6.02 ± 0.10	Ca06

2006; Caballero et al. 2007). There are other investigations that require a precise age determination, such as the evolution of the angular momentum due to discs and stellar winds (Eisloffel & Scholz 2007), disc dissipation (Hernández et al. 2007) and evolution of hot massive stars. In this Letter, I revisit a well known method for distance determination: the dynamical parallax (e.g. Russell 1928). I apply it to the σ Ori AB binary using state-of-the-art data and tools to determine its mass, age and heliocentric distance.

2 ANALYSIS AND RESULTS

The determination of the dynamical parallax of a binary of known orbital period, P , and angular semimajor axis, α , uses the Kepler’s third law and a power-law mass-luminosity relation (e.g. Reed 1984). In this Letter, I instead use the grids of theoretical models from the Geneva group (Schaller et al. 1992). On the contrary to other widely used grids, like those by the Lyon and Padova groups (Baraffe et al. 1998; Girardi et al. 2000), the Geneva grids tabulate absolute magnitudes in a large number of passbands and ages down to 1 Ma and are valid up to very high masses (i.e. $M > 10 M_\odot$). Although there are more binaries and binary candidates in the cluster (Caballero 2005; Kenyon et al. 2005; Caballero et al. 2006 and references therein), σ Ori AB is the only pair whose orbital parameters are known. Here, I have employed the parameters given by Hartkopf et al. (1996). The almost face-on orbit is characterised by a long period ($P = 155.3 \pm 7.5$ a), a close angular separation ($\alpha = 0.2642 \pm 0.0052$ arcsec) and a low eccentricity ($e = 0.051 \pm 0.015$). The orbital parameters are consistent with those of Heintz (1997; $P = 158$ a, $\alpha = 0.265$ arcsec, $e = 0.06$).

Using the standard units M_\odot , a (annum) and AU for $M_A + M_B$, P and the physical semimajor axis a , respectively, the Kepler’s third law takes the simple expression $(M_A + M_B)P^2 = a^3$. Accounting for $a = d \tan \alpha \approx d\alpha$, where d is the heliocentric distance in parsecs, and replacing the values of P and α from Hartkopf et al. (1996), then the third law for σ Ori AB can be written as:

$$M_A + M_B = 7.45 \cdot 10^{-7} d^3 \quad (1)$$

($M_{\text{total}} \equiv M_A + M_B$). At the *Hipparcos* distance $d = 352$ pc, the total mass of the binary would be about $32 M_\odot$, that is less than the classical value of $M_{\text{total}} \sim 40 M_\odot$, but is consistent with the value of $M_{\text{total}} \sim 30 M_\odot$ estimated by Caballero (2007a).

I tabulate in Table 1 the *BVRIH*-band magnitudes of both components in σ Ori AB, taken from the literature (ten Brummelaar et al. 2000 –tBr00–; Caballero 2006 –Ca06–; Caballero 2007a –Ca07a–). Except for the *B*-band

measurement, that was estimated from the Tycho-2 $B_T V_T$ magnitudes, all the data come from adaptive optics observations. The *Hipparcos* catalogue also tabulated the non-standard *H_P*-band magnitudes. The magnitudes and colours of both stars correspond to what it was expected of an O9.5V and a B0.5V at $d \sim 350$ pc.

I have computed through a simple minimisation method which are the most probable heliocentric distances for several cluster ages. In particular, I have looked for the minima of the following chi-square distributions:

$$\chi^2(d, \mathcal{M}_A, \mathcal{M}_B) = \chi_A^2(d, \mathcal{M}_A) + \chi_B^2(d, \mathcal{M}_B) \quad (2)$$

(for fixed ages and metallicities), where χ_A^2 and χ_B^2 are:

$$\chi_A^2 = \sum \frac{(m_{\lambda,A} - m_{\lambda,A}^*)^2}{\delta m_{\lambda,A}^2}, \quad \chi_B^2 = \sum \frac{(m_{\lambda,B} - m_{\lambda,B}^*)^2}{\delta m_{\lambda,B}^2} \quad (3)$$

($\lambda \equiv B, V, R, I, H$). $m_{\lambda,[A,B]}$ and $\delta m_{\lambda,[A,B]}$ are the *observed* apparent magnitudes and corresponding uncertainties of σ Ori A and B in Table 1, and $m_{\lambda,[A,B]}^* = m_{\lambda,[A,B]}^*(d, \mathcal{M}_{[A,B]})$ are the *theoretical* apparent magnitudes that a hypothetical star of mass $\mathcal{M}_{[A,B]}$ would have at an heliocentric distance d . To compute $m_{\lambda,[A,B]}^*$, I have used: (i) the *theoretical* absolute magnitudes $M_{\lambda,[A,B]}$ from the basic grids of non-rotating stellar models with solar metallicity ($Z = 0.020$), overshooting and OPAL opacities of the Geneva group, (ii) the colour excess $E(B - V) = 0.05$ mag of σ Ori AB from Lee (1968) and (iii) the interstellar extinction law parameters A_λ/A_V and R_V from Rieke & Lebofski (1985). In detail, I have used the grids with standard mass loss \dot{M} and ages 1.0, 2.0, 3.2, 4.9 and 10.0 Ma (Schaller et al. 1992 – Sc92) and high mass loss $2 \times \dot{M}$ and age 3.2 Ma (Meynet et al. 1994 – Me94). The models do not provide data for other ages less than 32 Ma. Caballero (2006) measured an average solar metallicity of solar-like stars in the σ Orionis cluster, $[\text{Fe}/\text{H}] = 0.0 \pm 0.1$ dex, which justifies the use of $Z = 0.020$.

For a fixed age (and metallicity), there is a one-to-one correspondence in the grids between $M_{\lambda,[A,B]}$ and $\mathcal{M}_{[A,B]}$ if both A and B stars are in the main sequence. For each heliocentric distance, there is only one corresponding total mass of the hypothetical binary, $\mathcal{M}_{\text{total}} \propto d^3$ (Eq. 1). If the mass of the primary, \mathcal{M}_A , is fixed, then the mass of the secondary is obtained from the simple expression $\mathcal{M}_B(d, \mathcal{M}_A) = \mathcal{M}_{\text{total}}(d) - \mathcal{M}_A$. To sum up, there is a value of χ^2 for each trio (d, \mathcal{M}_A , age). Because of the known spectral types of σ Ori A and B, I conservatively imposed that the masses of the primary and of the secondary should lie on the intervals $10 M_\odot \leq \mathcal{M}_A \leq 50 M_\odot$ and $1.5 M_\odot \leq \mathcal{M}_B \leq \mathcal{M}_A$, respectively. These constraints speed up the minimization but do not influence the results (see below).

Fig. 1 illustrates the χ^2 minimisation for an age of 3.2 Ma and standard mass loss. Top and bottom windows display different coverage resolutions of the (d, \mathcal{M}_A) plane. The results for normal and high mass loss for 3.2 Ma are almost identical. The plots for the other ages except for 10.0 Ma are quite similar, with the minimum shifted along the X axis (distance). There are no solutions (i.e. the masses of A and B simultaneously satisfy Eq. 1 and the above constraints) for $d \lesssim 250$ pc and $d \gtrsim 500$ pc. In addition, the 4.9 Ma models do not provide solutions for $d \gtrsim 370$ pc. Finally, there are no solutions at all for 10.0 Ma. At this

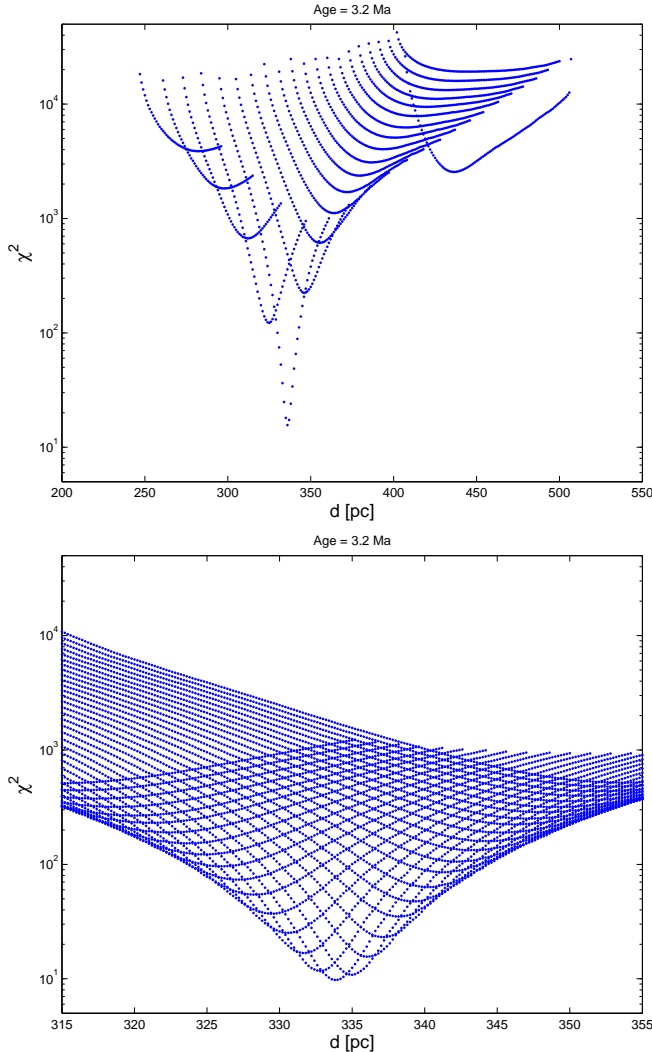


Figure 1. χ^2 vs. heliocentric distance for several masses of σ Ori A. The dotted lines indicate curves of constant mass. The basic grid of models is from Schaller et al. (1992), the age is 3.2 Ma and the metallicity is $Z = 0.020$. *Top window:* whole interval of heliocentric distance in steps of 1 pc from 200 to 550 pc and of mass of the primary in steps of $2 M_\odot$ from 10 to $50 M_\odot$. The minimum χ^2 is for $\mathcal{M}_A = 18 M_\odot$ ($d = 336$ pc). *Bottom window:* same as top window, but for intervals of heliocentric distance in steps of 0.2 pc and of mass of the primary in steps of $0.2 M_\odot$. The minimum in χ^2 is better constrained (cf. Table 2).

age, the primary has left the main sequence and got much brighter than the secondary.

The values of (d, \mathcal{M}_A) that minimise χ^2 for a given age and mass loss are provided in Table 2. The uncertainties in the values of d account for the error bars in the photometric data in Table 1 and in the orbital parameters P (5%) and α (2%) in Hartkopf et al. (1996), and the size of the steps in the high resolution minimisation ($\Delta d = 0.2$ pc). The uncertainty in the masses is set to the step size, $\Delta \mathcal{M}_A = 0.2 M_\odot$. The results would be identical if no mass constraints were set. For an age interval of 3 ± 2 Ma, the corresponding heliocentric distance interval is $d = 334^{+25}_{-22}$ pc. Distances larger than 400 pc and less than 290 pc are less likely for the 1–5 Ma age range; distances larger than 450 pc are highly unlikely

Table 2. Best fits of the dynamical parallax of σ Ori AB.

Mass loss	Age [Ma]	d [pc]	\mathcal{M}_A [M_\odot]	\mathcal{M}_B [M_\odot]	χ^2
$\dot{\mathcal{M}}$	1.0	346 ± 13	20.1 ± 0.2	11.7 ± 0.2	8.70
$\dot{\mathcal{M}}$	2.0	337 ± 13	18.3 ± 0.2	11.1 ± 0.2	9.38
$\dot{\mathcal{M}}$	3.2	334 ± 13	17.6 ± 0.2	10.8 ± 0.2	9.76
$\dot{\mathcal{M}}$	4.9	325 ± 13	16.0 ± 0.2	10.2 ± 0.2	10.56
$\dot{\mathcal{M}}$	10.0
$2 \times \dot{\mathcal{M}}$	3.2	333 ± 13	17.4 ± 0.2	10.8 ± 0.2	9.72

for all ages. Finally, I have determined the most probable masses of A and B for the *Hipparcos* parallax distance ($d = 352$ pc): $\mathcal{M}_A = 21.4 M_\odot$, $\mathcal{M}_B = 12.0 M_\odot$ for an age of 1 Ma. The minimum χ^2 for 1 Ma is an order of magnitude smaller than for the other ages tested, meaning that a binary age older than 1 Ma would be unlikely at the *Hipparcos* distance.

3 DISCUSSION

The theoretical effective temperatures that correspond to the optimal fits lie on the intervals $T_{\text{eff}} = 30.4\text{--}34.6$ kK for the primary and $T_{\text{eff}} = 25.2\text{--}27.5$ kK for the secondary. The hottest temperatures are for the youngest ages. These values are consistent with the expected T_{eff} for O9.5V and B0.5V stars, respectively (e.g. O9.5V: 30–35 kK – Popper 1980; Gulati, Malagnini & Morossi 1989; Castelli 1991; Vacca, Garmany & Shull 1996; Martins, Schaerer & Hillier 2005), and with previous measurements of the T_{eff} of σ Ori A (30.0–33.0 kK – Morrison 1975; Underhill et al. 1979; Morossi & Crivellari 1980; Repolust et al. 2005). The corresponding theoretical gravities ($\log g \sim 4.00\text{--}4.22$) are also normal for class V at such temperatures.

The minima of χ^2 in Table 2 are very sensitive to the variations of heliocentric distance and of mass: on the one hand, at fixed mass and age, a fluctuation of d of barely 30 pc results in a change of three orders of magnitude in χ^2 ; on the other hand, at fixed distance and age, a fluctuation of \mathcal{M}_A of barely $5 M_\odot$ results in a change of almost two orders of magnitude in χ^2 . The minima of χ^2 are, however, quite unresponsive to the variations of the age between 1.0 and 4.9 Ma (see last column in Table 2). A younger age gives a slightly better fit results and that favours a slightly larger distance ($d \sim 350$ pc). The results do not strongly suggest a younger age of 1 Ma, but they are useful in excluding an older age. The absence of a solution at 10 Ma agrees with previous upper limits on the ages of the Ori OB 1 b association from the presence of very early-type stars in the main sequence (Blaauw 1964) and of the σ Orionis cluster from spectral synthesis surrounding the Li I $\lambda 670.78$ nm line (Zapatero Osorio et al. 2002a).

The derived distance interval for 3 ± 2 Ma, $d = 334^{+25}_{-22}$ pc, is consistent with the canonical distance to the σ Orionis cluster of $d \sim 360$ pc, but is difficult to conciliate with the distance of 440 pc for 2.5 Ma that Sherry, Walter & Wolk (2004) used. The derived distance interval also deviates from very recent determinations of the distance to some elements in the Ori OB 1 complex. In particular, Terrell, Munari & Siviero (2007), using the eclipsing spectroscopic binary VV Ori close to Anilam (ϵ Ori) in Ori OB 1 b, and

Sandstrom et al. (2007), employing the Very Large Baseline Array in the Orion Nebula Cluster in Ori OB 1 a, have determined very accurate heliocentric distances of 388–389 pc (see also Menten et al. 2007). These values are also lower than the classical distance to the Ori OB 1 complex of ~ 440 pc from average *Hipparcos* parallax (Brown, Walter & Blaauw 1999; de Zeeuw et al. 1999). Because of projection effects and the large physical size of Ori OB 1 (Reynolds & Ogden 1979), σ Ori could be easily contained within the complex. Given their kinematic and spacial association, the σ Ori system and the young σ Orionis cluster are likely at the same heliocentric distance and also age, if one assumes that massive and low mass star formation in a cluster is coeval (Prosser et al. 1994; Massey, Johnson & Degioia-Eastwood 1995; Stauffer et al. 1997; see, however, Sacco et al. 2007). Recently, it has been suggested that the σ Orionis cluster is actually kinematically distinct from the Ori OB 1 b association (Jeffries et al. 2006), just as 25 Ori is distinct from Ori OB 1 a (Briceño et al. 2007).

If σ Ori AB were a hierarchical triple, as described in Section 1, it would be located at a larger heliocentric distance. The hypothetical companion to σ Ori A, to which I tentatively call σ Ori F, would be 0.5 mag fainter than the primary in the 370–493 nm interval according to Bolton (1974). This wavelength interval corresponds to the U , B Johnson bands. Taking into account $m_A = m_{A+F} + 2.5 \log \left(1 + 10^{-\frac{m_A - m_F}{2.5}} \right)$ and the difference $B_{A+F} - B_B$ in Table 1, then the apparent magnitudes in the blue band of the three components would be related to the combined magnitude B_{A+F} through: $B_A \approx B_{A+F} + 0.53$ mag, $B_B \approx B_{A+F} + 1.33$ mag and $B_F \approx B_{A+F} + 1.03$ mag. I have looked for the distances and theoretical masses whose corresponding apparent magnitudes match the $B_{[A,B,F]}$ relations and the Kepler’s third law, $(M_A + M_F) + M_B = 7.45 \cdot 10^{-7} d^3$. There are only a few solutions that simultaneously verify $T_{\text{eff},A} \approx 30.0\text{--}33.0$ kK and $T_{\text{eff},B} \approx 26.0\text{--}30.0$ kK, as expected from the spectral types of σ Ori A+F and σ Ori B. In the triple scenario, the F component would have an intermediate temperature between the A and B stars (roughly B0.0V) and would orbit very close to σ Ori A. The valid solutions are found for the narrow distance interval 370–400 pc and only for ages between 1.0 and 4.9 Ma. Although distances less than 290 pc and larger than 450 pc are ruled out again, the most probable distance to σ Ori under the triple hypothesis, $d \sim 385$ pc, agrees very well with those of VV Ori and the Orion Nebula Cluster. Further high-resolution spectroscopic studies are needed to ascertain the existence and characteristics of σ Ori F.

4 SUMMARY

I have determined the most probable heliocentric distances and masses of the components in the young binary σ Ori AB. The used methodology is an improvement of the dynamical parallax method using a χ^2 minimisation of observed and theoretical apparent magnitudes of A and B. The values range in the intervals $325 \text{ pc} \lesssim d \lesssim 346 \text{ pc}$, $16 M_\odot \lesssim M_A \lesssim 20 M_\odot$, $10 M_\odot \lesssim M_B \lesssim 12 M_\odot$ for 1–5 Ma. Ages and distances larger than or equal to 10 Ma and ~ 450 pc are excluded from the minimisation. The theoretical effective tem-

peratures of both components are consistent with the observed spectral types. Accounting for uncertainties in the orbital parameters and photometric data from the literature, the derived distance interval for age = 3 ± 2 Ma is $d = 334^{+25}_{-22}$ pc. The values of χ^2 are minimum for the largest distances within this interval, that translate into the youngest ages. If there were a third component, σ Ori F, in a tight orbit to σ Ori A, then the system could be at a larger heliocentric distance of about 385 pc.

The σ Ori star system is in the centre of the young σ Orionis cluster. The knowledge of the age and heliocentric distance of the cluster is fundamental for the study of the initial mass function down to the planetary regime and the evolution of discs and angular momentum in very young objects.

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REFERENCES

- Andrews S. M., Reipurth Bo, Bally J., Heathcote S. R., 2004, *ApJ*, 606, 353
- Baraffe I., Chabrier G., Allard F., Hauschildt P. H., 1998, *A&A*, 337, 403
- Béjar V. J. S., Zapatero Osorio, M. R., Rebolo, R., 1999, *ApJ*, 521, 671
- Béjar V. J. S., Martín E. L., Zapatero Osorio M. R., 2001, *ApJ*, 556, 830
- Blaauw A., 1964, *ARA&A*, 2, 213
- Bohannon B., Garmany C. D., 1978, *ApJ*, 223, 908
- Bolton C. T., 1974, *ApJ*, 192, L7
- Briceño C., Hartmann L., Hernández J., Calvet N., Vivas A. K., Furesz G., Szentgyorgyi A., 2007, *ApJ*, 661, 1119
- Brown A. G. A., de Geus E. J., de Zeeuw P. T., 1994, *A&A*, 289, 101
- Brown A. G. A., Walter F. M., Blaauw A., 1999, in *ASP Conf. Ser., The Orion Complex Revisited*, ed. M. J. McCaughrean & A. Burkert, eprint arXiv:astro-ph/9802054
- ten Brummelaar T., Mason B. D., McAlister H. A., Roberts L. C. Jr., Turner N. H., Hartkopf W. I., Bagnuolo W. G. Jr., 2000, *AJ*, 119, 2403
- Burnham S. W., 1892, *AN*, 130, 257
- Caballero J. A., 2005, *AN*, 326, 1007
- Caballero J. A., 2006, PhD thesis, Universidad de La Laguna, Spain
- Caballero J. A., 2007a, *A&A*, 466, 917
- Caballero J. A., 2007b, *AN*, 328, 917
- Caballero J. A., 2007c, *MNRAS*, in press, eprint arXiv:0710.1255
- Caballero J. A., Béjar V. J. S., Rebolo R., Zapatero Osorio M. R., 2004, *A&A*, 424, 857

- Caballero J. A., Martín E. L., Dobbie P. D., Barrado y Navascués D. 2006, *A&A*, 460, 635
- Caballero J. A., Béjar V. J. S., Rebolo R. et al., 2007, *A&A*, 470, 903
- Castelli F., 1991, *A&A*, 251, 106
- Conti P. S., Leep E. M., 1974, *ApJ*, 193, 113
- Eisloffel J., Scholz A., 2007, *Proceedings for IAU Symposium No. 243*, 2007, “Star-disk interaction in young stars”, eprint arXiv:0708.1479
- Franciosini E., Pallavicini R., Sanz-Forcada J., 2006, *A&A*, 446, 501
- Frost E. B., Adams W. S., 1904, *ApJ*, 19, 151
- Garmany C. D., Conti P. S., Massey P., 1980, *ApJ*, 242, 1063
- Girardi L., Bressan A., Bertelli G., Chiosi C., 2000, *A&AS*, 141, 371
- González-García B. M., Zapatero Osorio M. R., Béjar V. J. S., Bihain G., Barrado y Navascués D., Caballero J. A., Morales-Calderón M., 2006, *A&A*, 460, 799
- Greenstein J. L., Wallerstein G., 1958, *ApJ*, 127, 237
- Gulati R. K., Malagnini M. L., Morossi C., 1989, *A&AS*, 80, 73
- Hartkopf W. I., Mason B. D., McAlister H. A., 1996, *AJ*, 111, 370
- Heard J. F., 1949, *ApJ*, 109, 185
- Heintz W. D., 1974, *AJ*, 79, 397
- Heintz W. D., 1997, *ApJS*, 111, 335
- Henroteau F., 1921, *Pub. Dominion Obs. Ottawa*, 5, 45
- Hernández J., Hartmann L., Megeath T. et al., 2007, *ApJ*, 662, 1067
- Horch E. P., Robinson S. E., Meyer R. D., van Altena W. F., Ninkov Z., Piterman A., 2002, *AJ*, 123, 3442
- Humphreys R. M., 1978, *ApJS*, 38, 309
- Jeffries R. D., Maxted P. F. L., Oliveira J. M., Naylor T., 2006, *MNRAS*, 371, L6
- Kenyon M. J., Jeffries R. D., Naylor T., Oliveira J. M., Maxted P. F. L., 2005, *MNRAS*, 356, 89
- Lee T. A., 1968, *ApJ*, 152, 913
- van Loon J. Th., Oliveira J. M., 2003, *A&A*, 405, L33
- Martins F., Schaerer D., Hillier D. J., 2005, *A&A*, 436, 1049
- Massey P., Johnson K. E., Degioia-Eastwood K., 1995, *ApJ*, 454, 151
- Menten K. M., Reid M. J., Forbrich J., Brunthaler A., 2007, *A&A*, 474, 515
- Meynet G., Maeder A., Schaller G., Schaerer D., Charbonnel C., 1994, *A&AS*, 103, 97
- Miczaika G. R., 1950, *ApJ*, 111, 443
- Morrell N., Levato H., 1991, *ApJS*, 75, 965
- Morossi C., Crivellari L., 1980, *A&AS*, 41, 299
- Morrison N. D., 1975, *ApJ*, 200, 113
- Oliveira J. M., Jeffries R. D., Kenyon M. J., Thompson S. A., Naylor T., 2002, *A&A*, 382, L22
- Oliveira J. M., Jeffries R. D., van Loon J. Th., 2004, *MNRAS*, 347, 1327
- Oliveira J. M., Jeffries R. D., van Loon J. Th., Rushton M. T., 2006, *MNRAS*, 369, 272
- Perryman M. A. C., Lindegren L., Kovalevsky J. et al., 1997, *A&A*, 323, L49
- Popper D. M., 1980, *ARA&A*, 18, 115
- Prosser C. F., Stauffer J. R., Hartmann L., Soderblom D. R., Jones B. F., Werner M. W., McCaughrean M. J., 1994, *ApJ*, 421, 517
- Reed B. C., 1984, *JRASC*, 78, 83
- Reipurth Bo, Bally J., Fesen R. A., Devine D., 1998, *Nature*, 396, 343
- Repolust T., Puls J., Hanson M. M., Kudritzki R.-P., Mokiem M. R., 2005, *A&A*, 440, 261
- Reynolds R. J., Ogden P. M., 1979, *ApJ*, 229, 942
- Rieke G. H., Lebofsky M. J., 1985, *ApJ*, 288, 618
- Russell H. N., 1928, *AJ*, 38, 89
- Sacco G. G., Randich S., Franciosini E., Pallavicini R., Palla F. 2007, *A&A*, 462, L23
- Sandstrom K. M., Peek J. E. G., Bower G. C., Bolatto A. D., Plambeck R. L., 2007, *ApJ*, 667, 1161
- Sanz-Forcada J., Franciosini E., Pallavicini R., 2004, *A&A*, 421, 715
- Schaller G., Schaerer D., Meynet G., Maeder A., 1992, *A&AS*, 96, 269
- Scholz A., Eisloffel J., 2004, *A&A*, 419, 249
- Sherry W. H., Walter F. M., Wolk S. J., 2004, *AJ*, 128, 2316
- Stauffer J. R., Hartmann L. W., Prosser C. F., Randich S., Balachandran S., Patten B. M., Simon T., Giampapa M., 1997, *ApJ*, 479, 776
- Terrell D., Munari U., Siviero A., 2007, *MNRAS*, 374, 530
- Underhill A. B., Divan L., Prevot-Burnichon M.-L., Doazan V., 1979, *MNRAS*, 189, 601
- Vacca W. D., Garmany C. D., Shull J. M., 1996, *ApJ*, 460, 914
- Walter F. M., Wolk S. J., Freyberg M., Schmitt J. H. M. M., 1997, *MmSAI*, 68, 1081
- Zapatero Osorio M. R., Béjar V. J. S., Martín E. L., Rebolo R., Barrado y Navascués D., Bailer-Jones C. A. L., Mundt R., 2000, *Science*, 290, 103
- Zapatero Osorio M. R., Béjar V. J. S., Pavlenko Ya., Rebolo R., Allende Prieto C., Martín E. L., García López R. J., 2002a, *A&A*, 384, 937
- Zapatero Osorio M. R., Béjar V. J. S., Martín E. L., Rebolo R., Barrado y Navascués D., Mundt R., Eisloffel J., Caballero J. A., 2002b, *ApJ*, 578, 536
- Zapatero Osorio M. R., Caballero J. A., Béjar V. J. S. et al., 2007, *A&A*, 472, L9
- de Zeeuw P. T., Hoogerwerf R., de Bruijne J. H. J., Brown A. G. A., Blaauw A., 1999, *AJ*, 117, 354

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